

Human Habitation on the Moon: Closing the Loop - What is stopping us?

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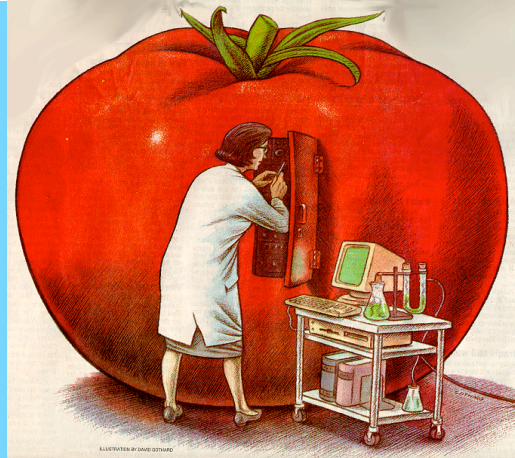


What is Preventing Significant Progress?

- **Plants and food production are required for ultimate loop closure.**
- **Complex systems require multi-disciplinary inputs to decision-making.**
- **Best-direction research pathways have not been identified.**
- **Not enough relevant data exist to make meaningful analyses and decisions.**



HARVEST



FOOD

WASTE

PLANTS



O₂

CO₂

HUMANS



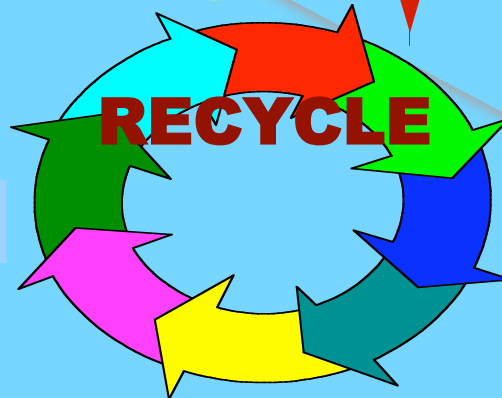
NUTRIENTS

H₂O

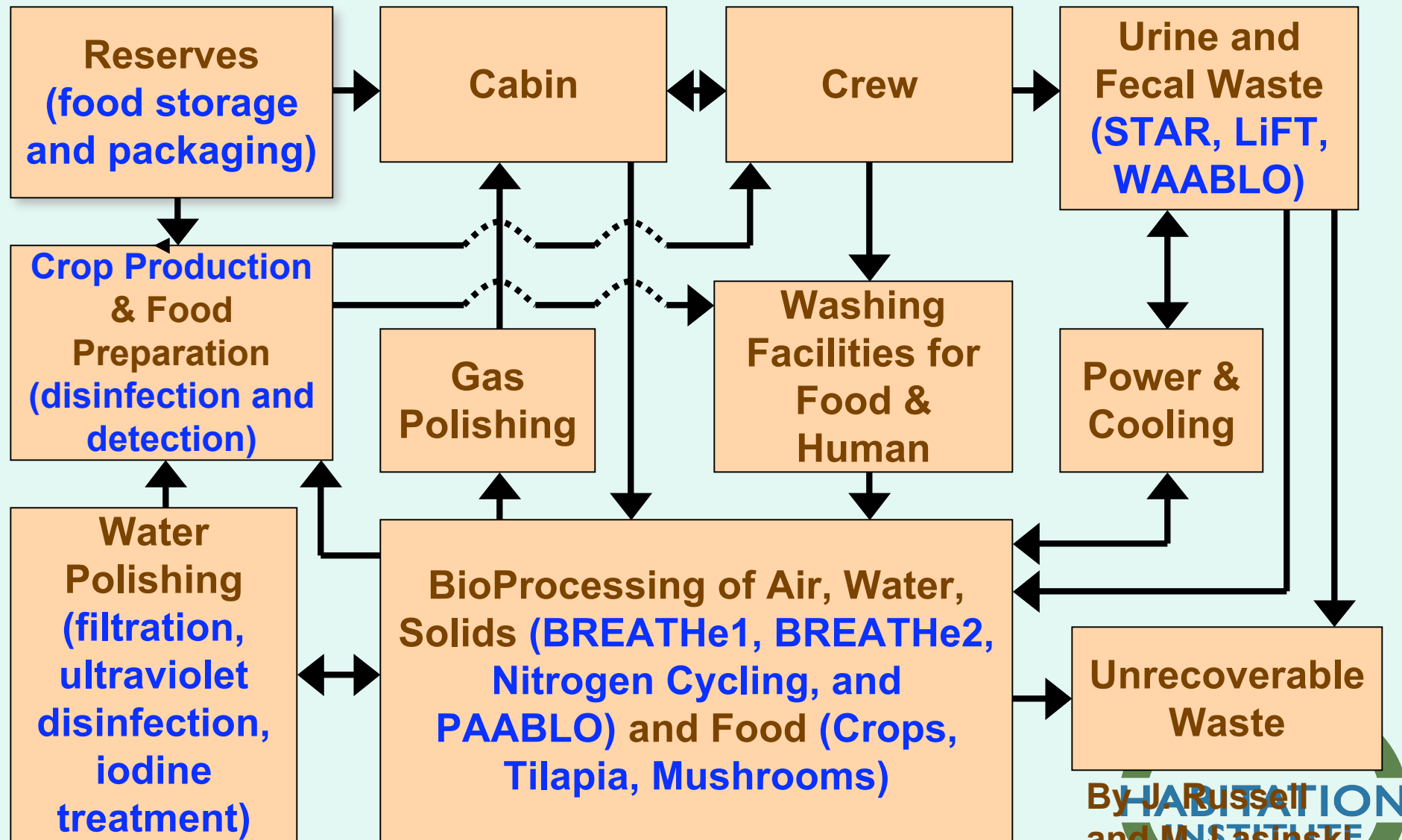
RECYCLE

WASTE

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Integrated RLSS





**The only
bioregenerative life
support system
known to humans?**



Plants are Required for Loop Closure

- PC technologies cannot generate food
- Only plants can generate edible biomass
- Air revitalization and water purification are defaults of crop production
- Packaged food has shelf-life limitations
- Resupply costs from Earth:
 - ~\$70K/lb for the moon
 - ~\$140K/lb for Mars



Role of Bioregenerative Components for Future Missions

Short Durations
(early missions)

Longer Durations

Autonomous
Settlements



Stowage and Physico-Chemical

Bioregenerative

Plant Growing Area



~1-5 m² total

~10-25 m² / person

~50 m² / person

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Regenerative Life Support Techniques

- Our current “picnic” approach is not feasible for extended duration missions (Moon/Mars base)
- Regeneration of life support elements is necessary

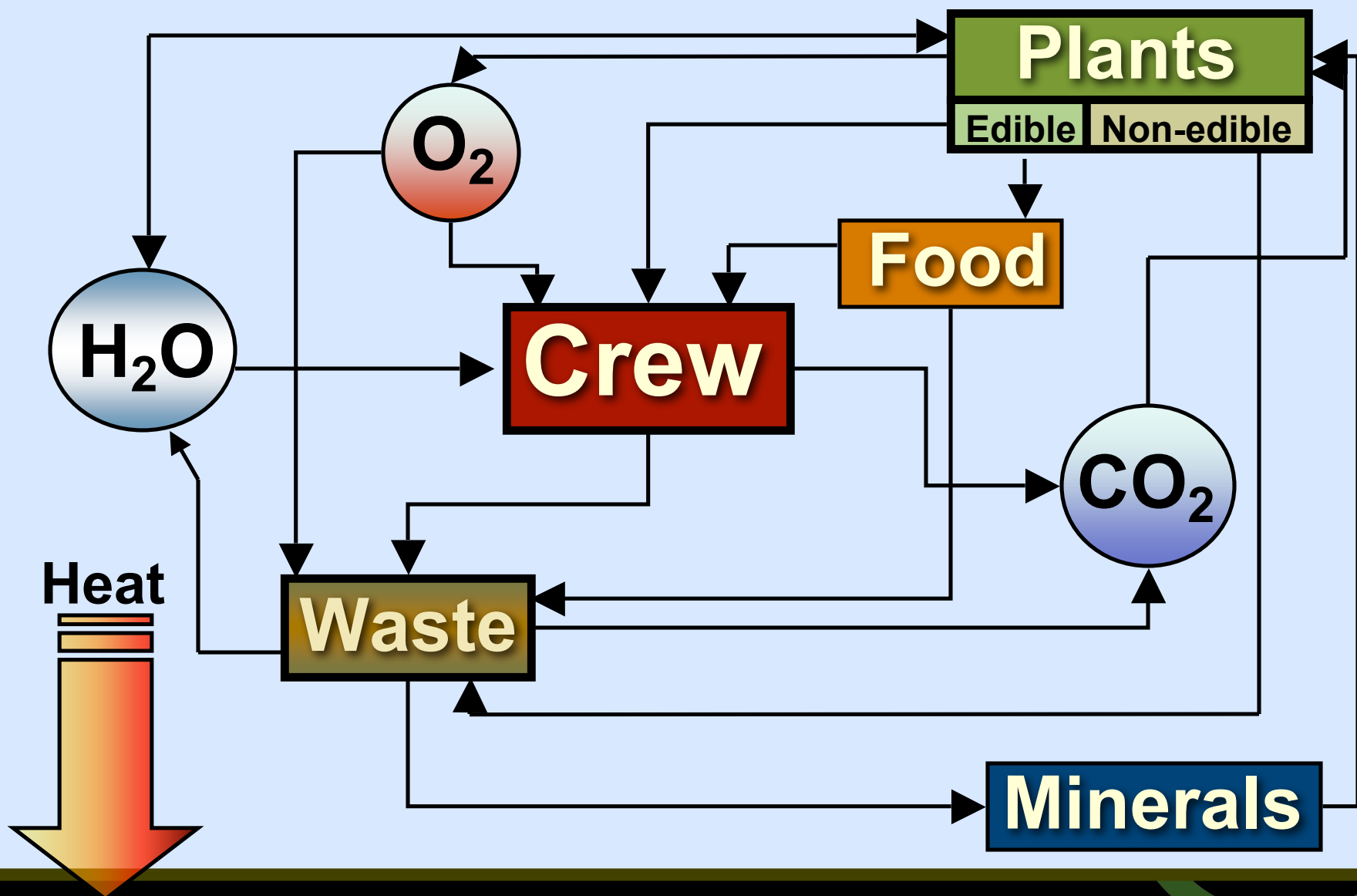


Loop-Closure Issues for Space Regenerative Life Support

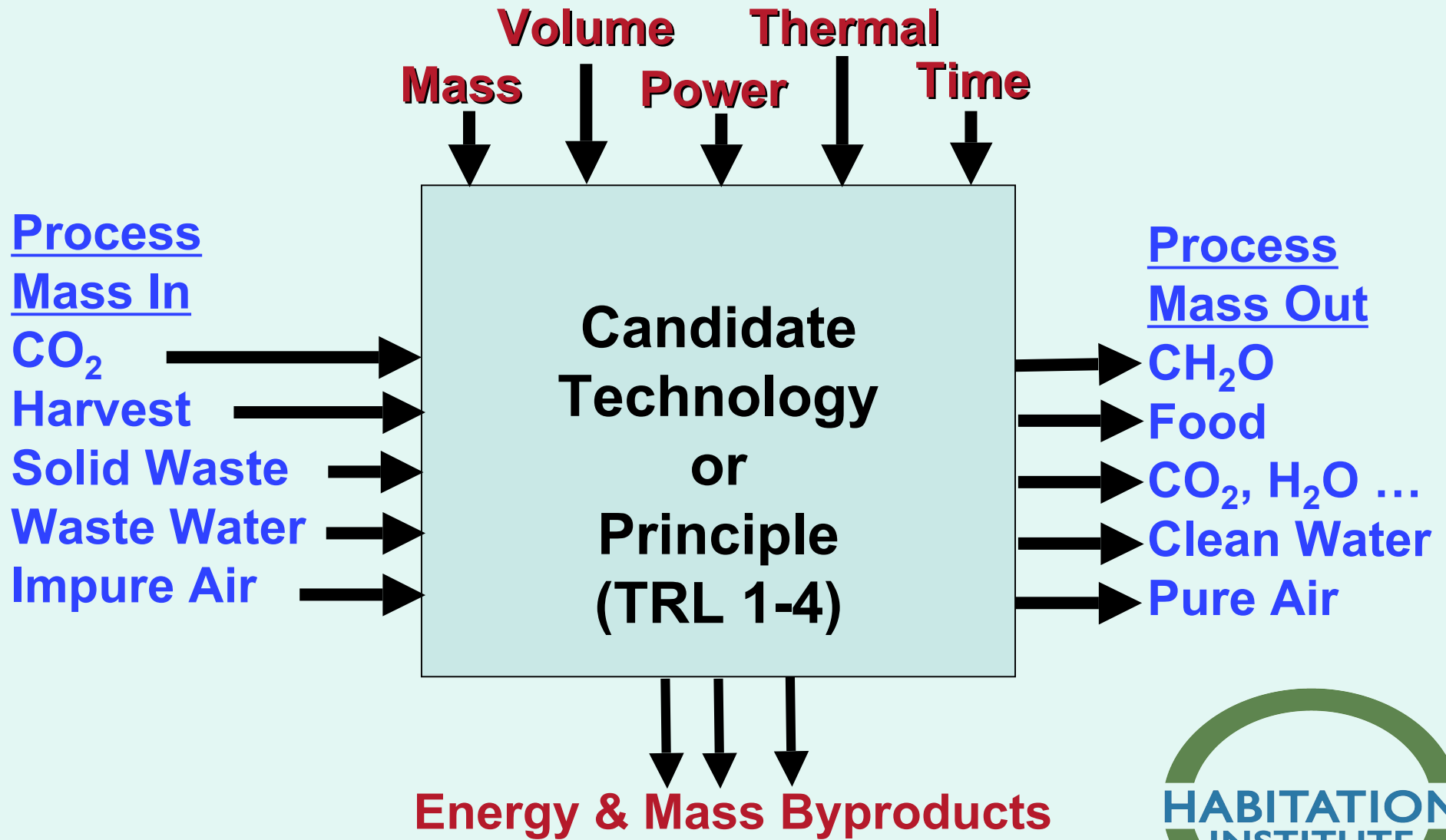
- **System must be closed with respect to mass but open with respect to energy**
- **Should minimize equivalent system mass (ESM) for each bioprocess**



Energy



Mass Conversion Inputs and Outputs



Constraints for Crop Production in Space:

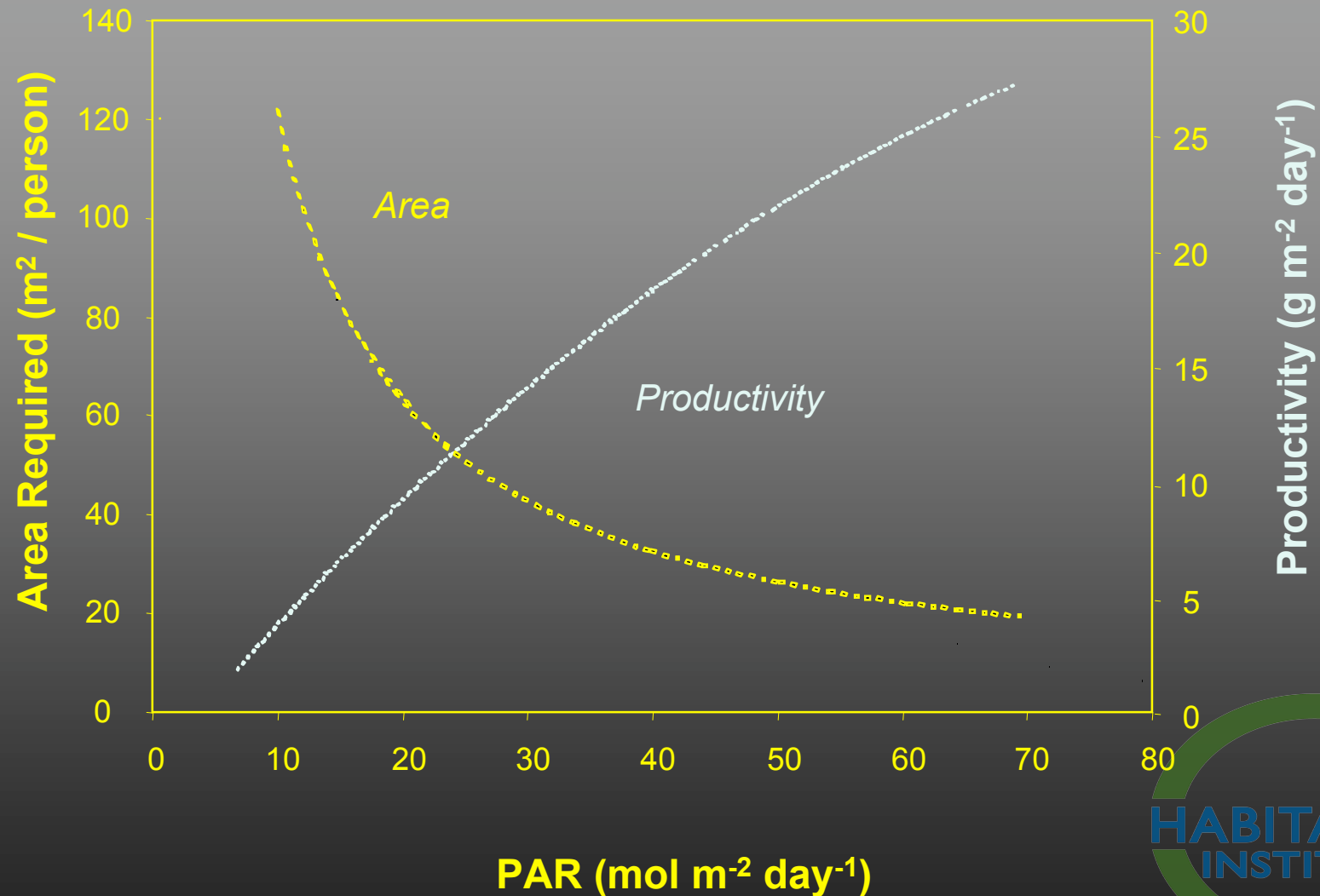
(“Economics” of Life Support)

- Energy Requirements
- System Mass
- System Volume
- Crew Time
- System Reliability

These apply for all life support technologies

For Plants, Lighting Dominates These Costs !

Effect of Light on Productivity and Crop Area Requirements



Continuing Challenges:

- Improved Horticultural Approaches
 - Mechanization / Automation
- More Complete Environmental Response Data
 - Define Optimal and Sub-Optimal Conditions
 - Crop Growth Models
- Systems Analysis / Trade Studies
 - Equivalent System Mass
- Additional Crop Species
- Better Adapted Cultivars
 - Dwarf, High Harvest Index, Nutritional Value
 - Engineer Cultivars to Fit System Constraints
- Improved Lighting Systems
 - More Efficient Electric Lamps and/or Solar Collectors
 - Improved Light Interception by Crops
 - Increased Photosynthetic Efficiency
- Food / Nutritional Aspects of CE-Grown Crops
- Waste Management, Recycling
 - Stirred Tank Reactors, Composting, Aquaculture



Other Factors in the Lunar Environment

High Radiation

Solar Wind, Solar Storms, Cosmic Rays

Microbial Ecology

Community Stability, Pathogens

Closed Atmospheric Issues

Volatile Organic Compounds

Waste Materials

Bioreactors, Composting, Nutrient Recycling



ENABLING SUSTAINABLE HABITATION ON THE MOON

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Best-direction research pathway: Focus on the significant limiting factor.

1: Reduce effective energy required to grow plant life on the Moon

Employ a Systems Biology Approach.

2: Grow plants in ways that conserve energy and other resources

3: Develop plants that use resources more efficiently



Objective 1: Reduce effective energy required to grow plant life on the Moon

- **Design LED lighting systems that target photosynthetic tissue specifically (Purdue/ORBITEC)**
- **Investigate hybrid lighting, including solar light capturing technology and electrical lighting sources (KSC/Dynamac)**
- **Investigate crop performance under mission-relevant hypobaric conditions (KSC/Dynamac)**
- **Target light to specific developmental stages of crops (Rutgers)**
- **Integrate multi-institutional results at Purdue to identify optimal energy scenario**
- **Conduct trade studies to examine inputs and outputs of various combinations (KSC/Dynamac)**



Objective 2: Grow plants in ways that conserve energy and other resources

- **Optimize growth environments using photosynthetic gas-exchange tool (light, temperature, CO₂) - (Purdue)**
- **Optimize tomato production in a controlled environment by manipulating light environments including photoperiod and intensity (Rutgers)**
- **Integrate results from above tasks to identify the best method for growing low-input, high-output plants (Purdue + Rutgers)**
- **Trade study of plant growth in lunar regolith compared with hydroponics (KSC/Dynamac)**



Objective 3: Develop plants that use resources more efficiently

- **Screen existing lines of tomatoes for biomass accumulation, lycopene production and stress tolerance (NCSU)**
- **Investigate wild varieties of tomato to transfer stress tolerance traits into domesticated cultivars (NCSU)**
- **Create tomato cultivars that are high in antioxidants and low in anti-metabolites (NCSU)**
- **Over-express genes that affect sink strength driving greater biomass accumulation in fruit under limited conditions (Rutgers)**
- **Utilize controlled-environment/gas-exchange integration tool to identify most effective modified plants within optimizing environments (Purdue + NCSU + Rutgers)**





Formed in May 2006, the Habitation Institute (HI) is a multi-institutional scientific partnership composed of universities and industry focused on the development and testing of technologies to support human activities within controlled environments on Earth and in space.

HABITATION INSTITUTE

A Memorandum of Understanding (MOU) was signed between partnership members and intended as a statement of principles under which Habitation Institute Advisory Panel Members agree to collaborate in refining the mission and goals of the Institute.

North Carolina State, Rutgers, Purdue, Florida, Cornell, Arizona, Texas A&M, Utah State, Dynamac Corporation



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Base Camp Sustainability Workshop, September 2007

Sponsored by the Army Research Office Environmental Sciences Division, the purpose of the workshop was to:

- Identify basic research questions that might have application to positively change forward base camp operations and shorten deployment times.
- Identify recent basic research developments that have the potential to benefit current base camp operations.

Criteria used to identify research questions:

- The research must be basic.
- No major investment is being made by other agencies in regards to the basic research.
- The research was required be scientifically relevant to the needs of Habitation Science in the DoD context.

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Technology Approaches to Current and Future Base Camp Sustainability

Final report of a Workshop held
September 12-14, 2007 in Raleigh, NC



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INTRODUCTION

Available technology can support human crews in space for short or indefinite duration missions as long as resupply is readily available, [picnic approach](#). Crewed space missions rely on resupply from Earth for some or all of the required consumable resources (oxygen, water, food). Re-supplying future missions beyond low Earth orbit will be even more difficult and expensive.



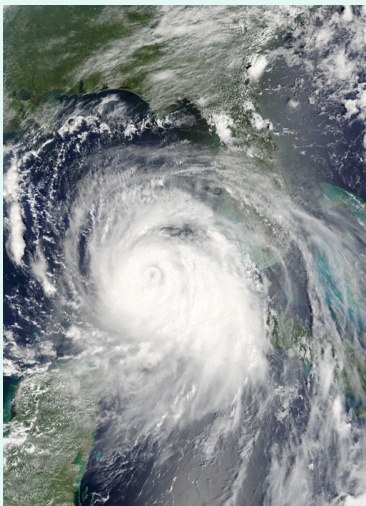
Habitation Science

Earth and Space Applications



Research and development has taken place across different communities seeking complementary technological solutions.

These communities include, but are not limited to: the military, with its need for rapidly deployable and/or long term base camps in the military theater; space exploration, with its need to support humans in the utterly inhospitable space environment; disaster recovery, with its need for small and large scale supply of basic human needs; and green/healthy building design.



The Habitation Institute seeks to provide cross-cuttings benefits to these communities providing a wide range of spin-off benefits to life on Earth, from solutions for solid-waste management and global-warming mitigation to better designs for more efficient buildings and workspaces.



Atmospheric Pressures for Plants in Space:

Advantages for Low Pressures

- **Reduced Structural Mass**
- **Reduced Gas Leakage (and Resupply)**
- **Wider Selection for Transparent Materials**

